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COLDEX-86: PHYSICAL WORK CAPACITY DURING PROLONGED COLD WATER IMMERSION AT 6.1 msw

T. J. Doubt
D. J. Smith

Naval Medical Research
and Development Command
Bethesda, Maryland 20889-5044

Department of the Navy
Naval Medical Command
Washington, DC 20372-5210

NOTICES

TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

LARRY W. LAUGHLIN
CAPT, MC, USN
Commanding Officer
Naval Medical Research Institute

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Response to submaximal leg exercise was quantified in 16 U.S. Navy divers who performed whole body immersions in 5 °C water for periods of up to 6 h. Divers wore passive dry suit thermal protection. Immersions were done during the course of 5-day air saturation dives at a depth of 6.1 msw (20 fsw). Each diver participated in 2 saturation dives. Two immersions were conducted per dive, one beginning at 1000 h, and one beginning at 2200 h; there was a period of 54 h between immersions. During the second saturation dive the presentation of immersion times was reversed.

The subjects performed leg exercise on a cycle ergometer for 3 min each at workloads of 50, 70, and 90 watts (W). Heart rate (HR) and O_2 consumption ($\dot{V}_{O_2}$) were measured during the last minute at each workload. The study was divided into 2 series. In Series 1 eight subjects performed the submaximal exercise each hour, beginning at the first hour

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of immersion to assess temporal changes in HR and $\dot{V}_{O_2}$ during the course of immersion. In Series 2, 8 divers performed the exercise only at the 3rd and 6th hour of immersion to simulate a mission scenario where the divers would be at rest for 3 h prior to performing work, rest again for 3 h, and then repeat the exercise paradigm.

Compared to control data obtained under dry conditions, exercise HR at each workload during the first hour of immersion was higher due to resistance of the dry suit and the water resistance on leg movement. With continued immersion there was a progressive uniform increase in HR at each workload, with no change in the slope of HR vs. workload. By the 6th h, peak exercise HR was 80-85% of the divers' maximum HR; suggesting that endurance would be reduced. No significant differences in HR or $\dot{V}_{O_2}$ with exercise were found between immersions beginning at 1000 or at 2200.

Resting $\dot{V}_{O_2}$ increased linearly with time of immersion, due to a thermogenic response. Exercise $\dot{V}_{O_2}$ at 50 W also increased linearly at the same rate as resting values, indicating that thermogenesis was not fully compensated at this light workload. Thus, work $\dot{V}_{O_2}$ (exercise - rest) did not change with immersion time. Exercise $\dot{V}_{O_2}$ at 70 and 90 W did not vary significantly during the 6 h immersions, leading to an apparent decrease in work $\dot{V}_{O_2}$. These findings suggest that either thermogenesis was compensated at these workloads, or an increase in the anaerobic cost of work occurred that would not be reflected in $\dot{V}_{O_2}$ measurements.

Divers in Series 2 who were at rest for the first 3 h of immersion had similar exercise responses at the 3rd hour to the subjects of Series 1 who performed hourly exercise. However, at the 6th hour of immersion Series 2 subjects had a larger HR values than those of Series 1.

The results of this study indicate that the ability to perform exercise declines linearly with time of immersion in cold water in divers wearing dry passive thermal protection. Decrements in performance were associated with an average decrease in rectal temperature of 1 °C and a 17% reduction in plasma volume. Diurnal differences did not occur. Prolonged rest prior to exercise had little effect on exercise response to 3 h, but subsequent rest periods led to marked increases in exercise HR.

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INTRODUCTION

It is well established that exposure to cold water can significantly reduce physical and mental performance (1,2,3). Extremities immersed in cold water exhibit a reduction in muscular strength (4,5). Exercise during whole body immersion in cold water is associated with reductions in aerobic power and O_2 cost of work (6,7,8,9).

Exposure to cold air results in diuresis that can lead to dehydration (10), which in turn causes decrements in physical performance. Immersion also results in diuresis (11), and subjects exercised under these conditions have a lower work tolerance (4,9,11,12). Most of the immersion studies are conducted without thermal protection for the subjects. Thus, these studies are constrained to either moderate water temperature or of short duration.

Practical diving situations are most commonly done in cold water with divers wearing some form of thermal protection. Furthermore, operational diving often requires nighttime in-water exposure times longer than the 1-3 h noted with most immersion studies.

The overall objective of the present study was to quantify the exercise response in thermally protected divers submerged in 5 °C water for periods of up to 6 h. Efforts were made to determine changes occurring during the course of immersions, and to contrast differences between immersions conducted during the day and immersions conducted at night. Furthermore, the effect of 3 h rest during immersion before the onset of exercise was compared to hourly exercise periods to determine if prolonged inactivity significantly influenced exercise response.

METHODS

Sixteen fit male subjects (12 U.S. Navy First Class Divers, 4 U.S. Navy SEALs) participated in the study after signing informed consent documents. The physical characteristics of the divers are presented in Appendix A.

Technical aspects of the study are presented fully in another NMRI Technical Report (13). Briefly, each diver participated in two 5-day air saturation dives at a storage depth of 6.1 msw (20 fsw), with an interval of 9 days between the end of one dive and the start of the next dive. During each saturation dive, each subject performed two whole body immersions: one beginning at 1000 h (termed AM) and one beginning at 2200 h (termed PM). A period of 54 h elapsed between immersions. The presentation of the immersion times was reversed on the second dive to prevent ordering effects. Thus, each subject performed 4 immersions: two AM and two PM.

Immersions were conducted in the wet pot of the chamber complex at an effective depth of 22 fsw (20 fsw storage depth ± 2 fsw over the subject's head). Two divers were immersed each time. Each diver wore passive thermal protection in the form of a dry suit with undergarment insulation (mean insulation = 1.4 clo), dry suit hood, dry gloves, and a full face mask. Inspired air temperature was within 0.1 °C of water temperature. Each subject was instrumented with ECG leads, heat flux sensors, and skin temperature thermistors. Immersions, intended to last 6 h, were aborted before 6 h in case of equipment or medical problems. Overall, 43% were completed for the full 6 h and 92% lasted at least 3 h. The mean time of all immersions was 4h 37m.

Leg exercise was performed in the seated position using an electronically braked ergometer. Exercise was done at a hip flexion of about 120-130 degrees, and a pedalling frequency of 50 rpm. Work was performed for 3 min each at ergometer workload settings of 50, 70, and 90 W. Heart rate (HR) data were collected over the last 20 sec at each workload. Oxygen consumption ($\dot{V}_{O_2}$) was measured during the last minute of each workload using open circuit spirometry (13). Resting $\dot{V}_{O_2}$ was measured every 10 min.

The study was divided into two series. Series 1 was comprised of 8 subjects who performed leg exercise once each hour, beginning one hour after the start of immersion. Data from this series was used to quantify temporal exercise changes during immersion. Series 2 was comprised of the other 8 subjects, who performed the exercise only twice: at the 3rd and 6th hour of immersion. Data from this series was used to determine if 3 h of rest in cold water would have an adverse effect on subsequent exercise capacity, as opposed to the effect of hourly work periods.

The linear relationship between HR and workload was analyzed to determine if cardiac responsiveness was altered by immersion, as judged by changes in the slope of this relationship. In addition, the linear form of HR vs workload was extrapolated to a HR of 170 to determine the theoretical workload that would be required to produce a HR of 170. This workload value, known as PWC170, is a standard measure of exercise capacity derived from submaximal workloads (14). Use of PWC170 afforded the advantage of producing a single value representative of work capacity at a given time during immersion.

Slopes of HR versus workload, PWC170 versus time of immersion, and $\dot{V}_{O_2}$ versus time were assessed by least-squares linear regression techniques. Differences between AM and PM values of these slopes were statistically evaluated by a paired student's t-test. This test was also applied to determine differences between dry and 1st hour immersion values of PWC170. Changes in HR and $\dot{V}_{O_2}$ during each hour of immersion were statistically assessed by a one-way ANOVA for repeated measures, using the Neuman-Keuls

Multiple Range test to define the significance of hourly differences. Differences between AM and PM immersions or between Series 1 and Series 2 were determined by two-way ANOVA for repeated measures with the multiple-range test. Statistical significance limits were set at p values < 0.05. All averaged data are presented as the mean ± standard error (SE).

RESULTS

SERIES 1, EXERCISE EACH HOUR

Individual values of HR and $\dot{V}_{O_2}$ for Series 1 are presented in Appendix B (AM immersions) and C (PM immersions). Figure 1 illustrates mean HR values for the first hour of the AM immersions contrasted to HR data obtained under dry control conditions. Not unexpectedly, the immersion curve was displaced upward, reflecting the added effort imposed by the combination of dry suit resistance and resistance of leg movement through the water. The slope of the immersion curve was 0.8 ± 0.1 bpm/watt, which was significantly greater than the slope obtained during dry conditions (0.4 ± 0.1, p<0.001). The slope of the same relationship obtained during the first hour of PM immersions (0.7 ± 0.1) was not different from the AM immersion value.

The combination of higher HR at each workload and greater slope during the first hour of immersion resulted in lower calculated values of PWC170. Compared to the dry control value (3.48 ± 0.22 W/kg), PWC170 for both AM and PM immersions was significantly reduced (1.76 ± 0.43, and 1.81 ± 0.48 respectively, each p<0.001 from dry condition). No meaningful difference in PWC170 existed between the AM and PM values.

Figure 2 presents the mean exercise HR data from AM immersions of Series 1. At a given workload, the HR values became progressively higher during the course of immersion. There was, however, no significant change in the slope of HR versus workload, indicating that cardiac responsiveness to increasing

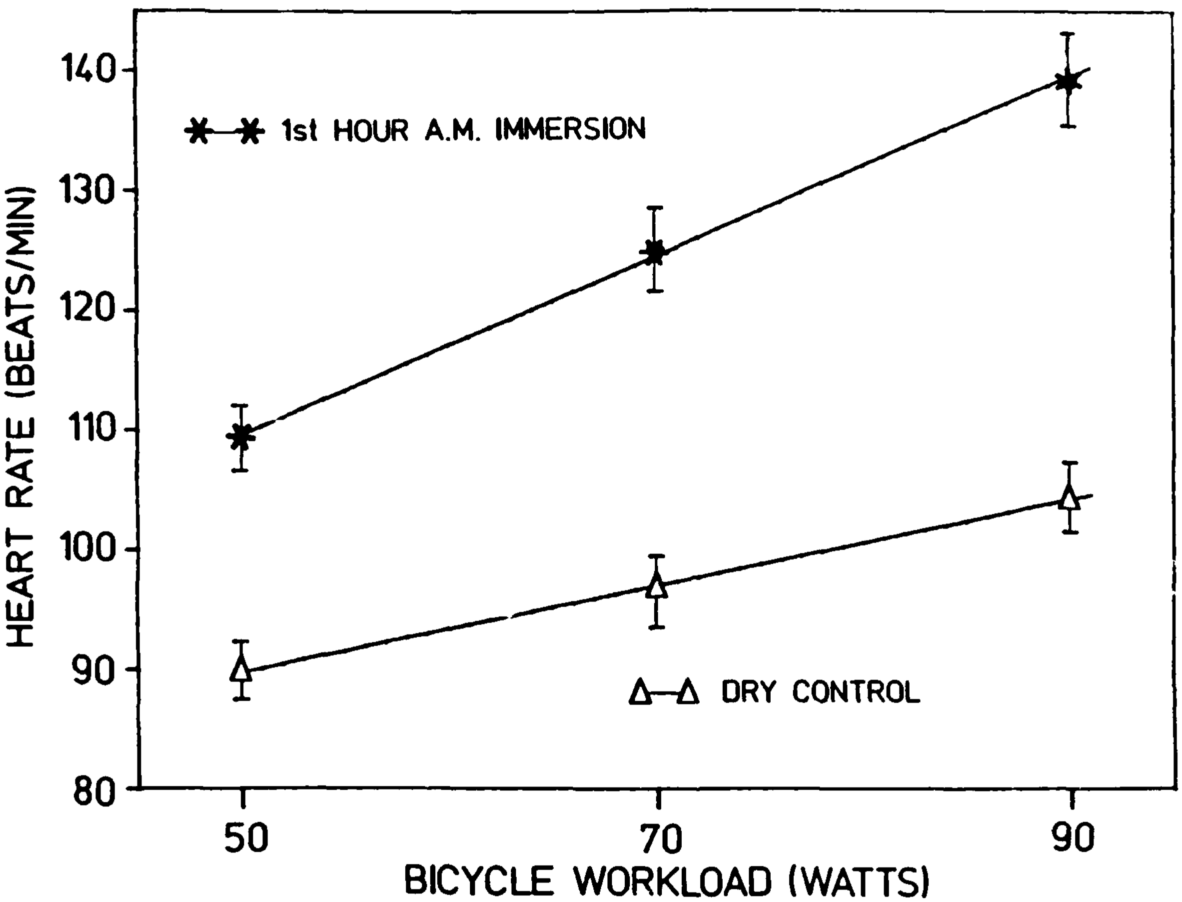

Figure 1. Mean (± SE) of heart rate values during last min of exercise at each workload in 8 divers of Series 1. Dry control was prior to start of dive series. First hour of A.M. immersion resulted in greater slope of HR vs workload, as well as upward displacement of the relationship.

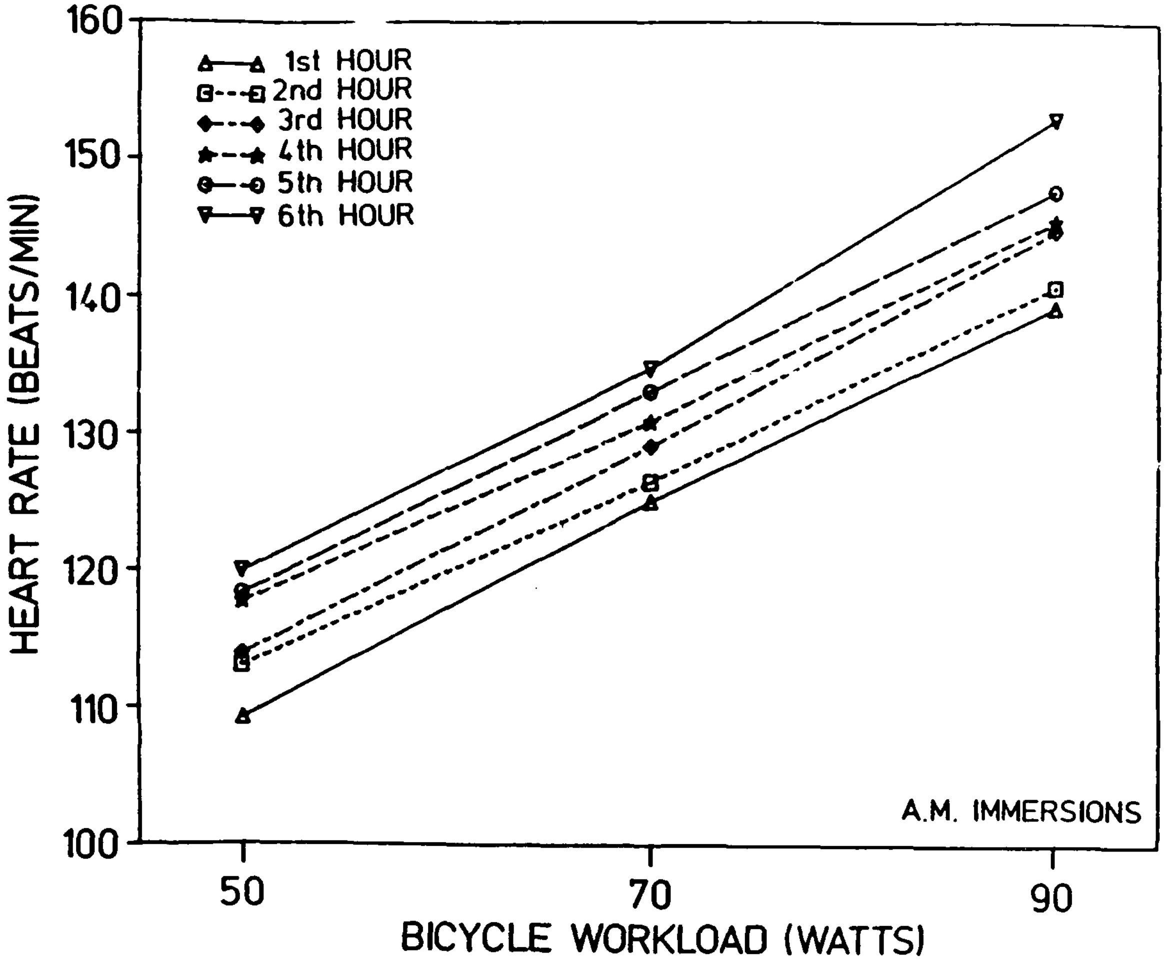

Figure 2. Mean heart rate values during last minute of exercise at each workload of 8 divers from Series 1 for immersions beginning at 1000 (A.M.). Linear relation between HR and workload preserved throughout immersion, but upward shift in HR at each workload represents decline in work capacity.

workloads was not altered by time of immersion. The peak HR achieved during the 6th hour of exercise (153 ± 5 bpm) represented a value equivalent to about 80-85% of subject's maximum HR obtained under dry laboratory conditions. Figure 3 illustrates that the same finding was obtained during PM immersions.

Figure 4 presents PWC170 values calculated each hour for both AM and PM immersions using only data obtained from subjects who completed the full 6 hour immersion profiles. There was a significant decrease in PWC170 with time for both AM (0.08 ± 0.03 W/kg/hr, F=14.57, p=0.002) and PM immersions (0.12 ± 0.03, F=21.52, p=0.001). No significant difference in slopes was detected between AM and PM immersions. The percent change from the 1st to the 6th hours of immersion were -16 and -19%, respectively.

Figure 5 indicates that resting $\dot{V}_{O_2}$ during AM immersions increased at the rate of about 0.5 ml/min/kg per hour. This rise in $\dot{V}_{O_2}$ could be attributed to a thermogenic response to cold, particularly through shivering. The figure also indicates that exercise at 50 W produced the same linear rise in $\dot{V}_{O_2}$ with the result that the work $\dot{V}_{O_2}$ ($\dot{V}_{O_2}$ at 50 W - rest) did not change with time of immersion. In contrast, the regression of $\dot{V}_{O_2}$ data at both 70 and 90 W vs. time showed essentially no change. This probably means that the increased $\dot{V}_{O_2}$ required by the 50 W exercise was not sufficient to meet thermogenic requirements, thus the $\dot{V}_{O_2}$ value was comprised of resting, thermogenic, and exercise components. At the higher workloads, the thermogenic requirement was likely met, and the $\dot{V}_{O_2}$ value was comprised of only resting and exercise components.

Figure 6 presents the $\dot{V}_{O_2}$ data for the PM immersions. The linear increases in $\dot{V}_{O_2}$ at rest and at 50 W were not significantly different from those obtained for AM immersions. Likewise, $\dot{V}_{O_2}$ did not change linearly with time at 70 and 90 W.

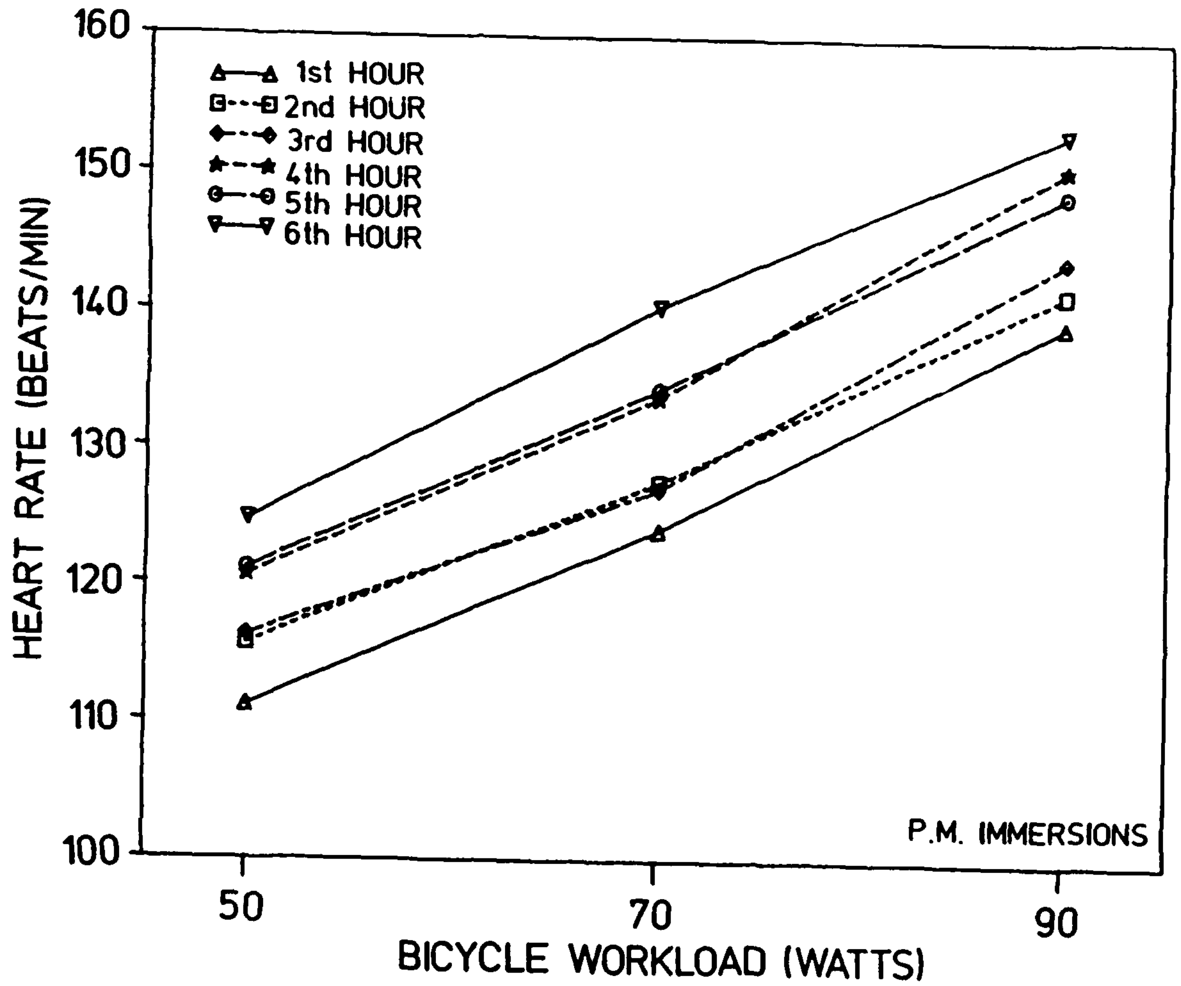

Figure 3. Mean heart rate values of 8 divers for immersions beginning at 2200 (P.M.). Upward displacement of HR at each workload with time indicates decline in worn capacity.

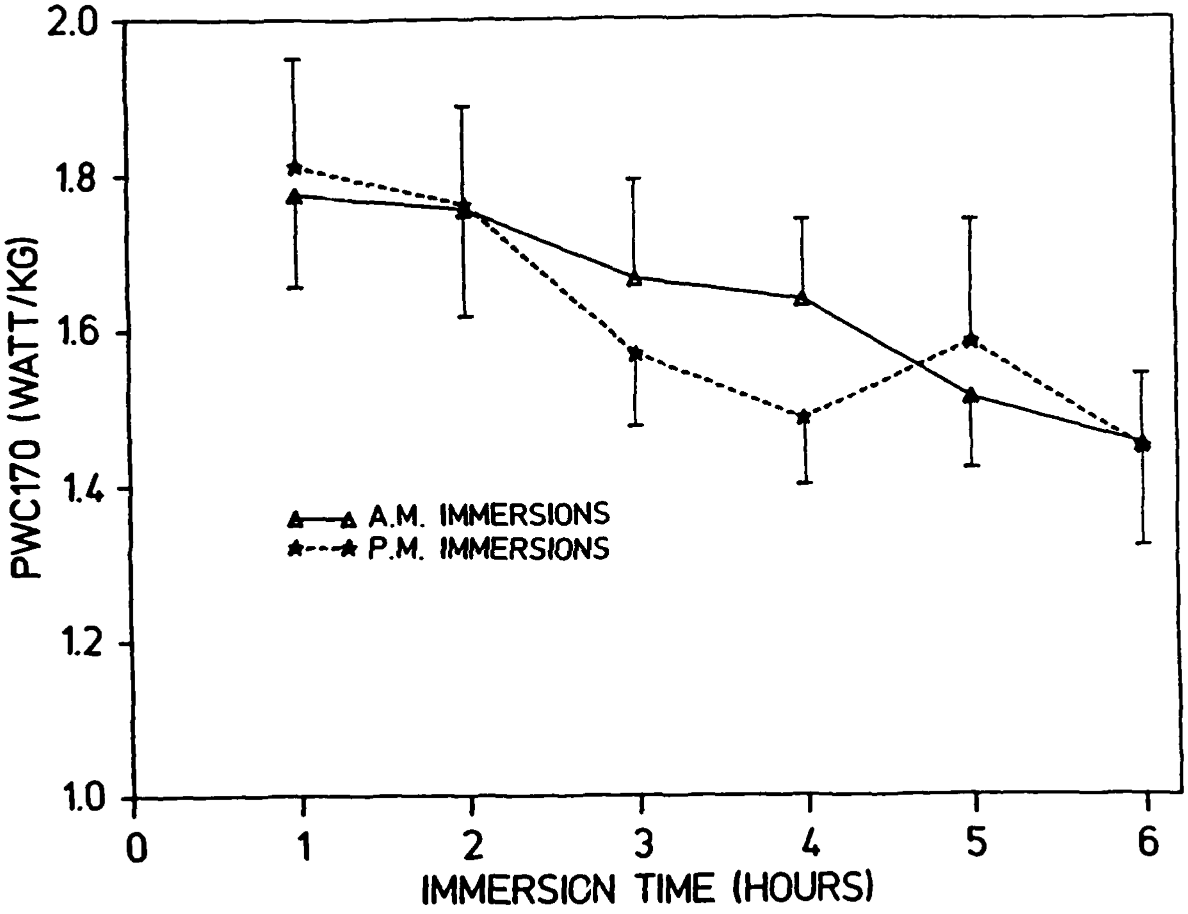

Figure 4. Linear decline in PWC170 was the same for both A.M. and P.M. immersions. Data were derived from those subjects of Series 1 who completed the full 6 hour immersion profile.

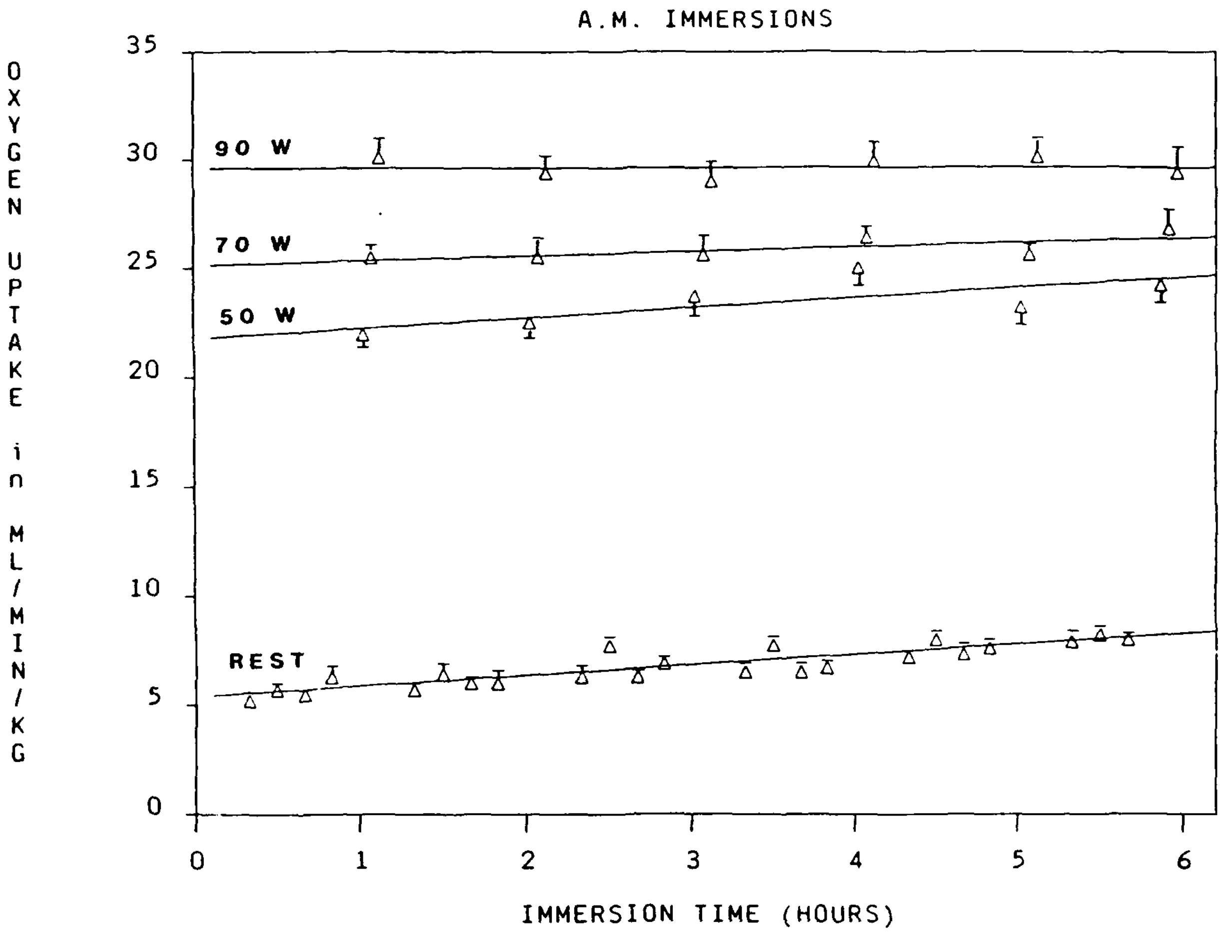

Figure 5. Oxygen consumption values for all subjects during rest and exercise at 50, 70, and 90 W during AM immersions. Solid lines are linear regressions for each of 4 conditions.

	slope	intercept	
REST $\dot{V}_{O_2}$	0.48 ± 0.05	5.41 ± 0.18	F=78.36, p<0.001
50 W $\dot{V}_{O_2}$	0.46 ± 0.19	21.80 ± 0.70	F= 5.86, p<0.025
70 W $\dot{V}_{O_2}$	0.21 ± 0.19	25.16 ± 0.70	F= 1.20, p>0.100
90 W $\dot{V}_{O_2}$	0.00 ± 0.22	29.62 ± 0.82	F= 0.25, p>0.100

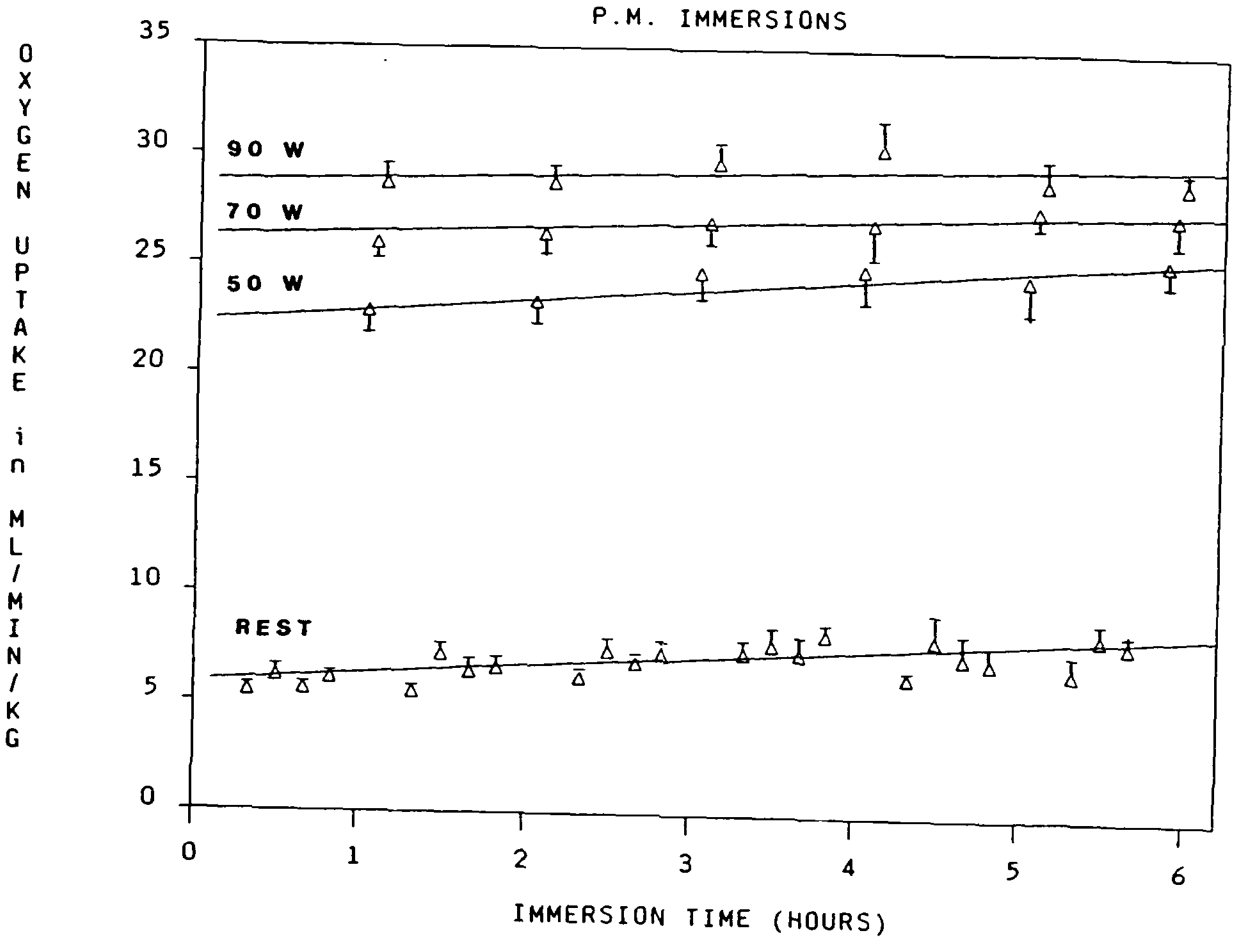

Figure 6. Oxygen consumption values for PM immersions. Solid lines are linear regressions for each condition.

	slope	intercept	
REST $\dot{V}_{O_2}$	0.41 ± 0.09	5.91 ± 0.25	F=21.82, p<0.001
50 W $\dot{V}_{O_2}$	0.52 ± 0.32	22.39 ± 1.09	F= 2.53, p<0.05
70 W $\dot{V}_{O_2}$	0.23 ± 0.33	26.30 ± 1.06	F= 0.52, p>0.10
90 W $\dot{V}_{O_2}$	0.17 ± 0.26	28.79 ± 0.90	F= 0.40, p>0.10

The decline in aerobic work $\dot{V}_{O_2}$ at 90 W versus immersion time is shown in Figure 7 for AM and PM immersions. Since the energy requirement to do external work did not change during immersion (e.g., suit/water resistance did not change, workload was always 90 W), the graph likely reflects two simultaneous processes. One process is that the metabolic heat produced at this higher workload might fully compensate shivering thermogenesis, and thus the true resting $\dot{V}_{O_2}$ would be lower with no change in aerobic work. The second process is that the anaerobic contribution to exercise might increase with time at this workload, and not be evident in $\dot{V}_{O_2}$ measurements leading to a genuine decrease in aerobic work.

Regardless of how the two processes might interrelate, the amount of energy required to explain the decreases in work $\dot{V}_{O_2}$ can be estimated from differences in exercise $\dot{V}_{O_2}$, since consumption of 1 ℓ of O_2 yields about 20,930 joules (J). For AM immersions, the work-related $\dot{V}_{O_2}$ during the last minute at 90 W was 0.207 ± 0.074 ℓ less at the 6th hour than at the 1st hour of immersion ($p<0.05$). This difference represents about 4300 J less of aerobic energy expended during the 6th hour to accomplish the same external work done during the first hour. Similarly, the difference for PM immersions averaged 0.195 ± 0.082 ℓ O_2 ($p<0.05$), or about 4,080 J. These energy values represent the net balance between the shivering thermogenesis energy requirement compensated by exercise metabolic heat and the energy liberated by any increase in anaerobic metabolism (e.g., lactate production).

SERIES 2, EXERCISE 3RD AND 6TH HOUR

In Series 2 the subjects performed exercise only at the 3rd and 6th hour of immersion. Individual data are presented in Appendix D (AM immersion) and E (PM immersions).

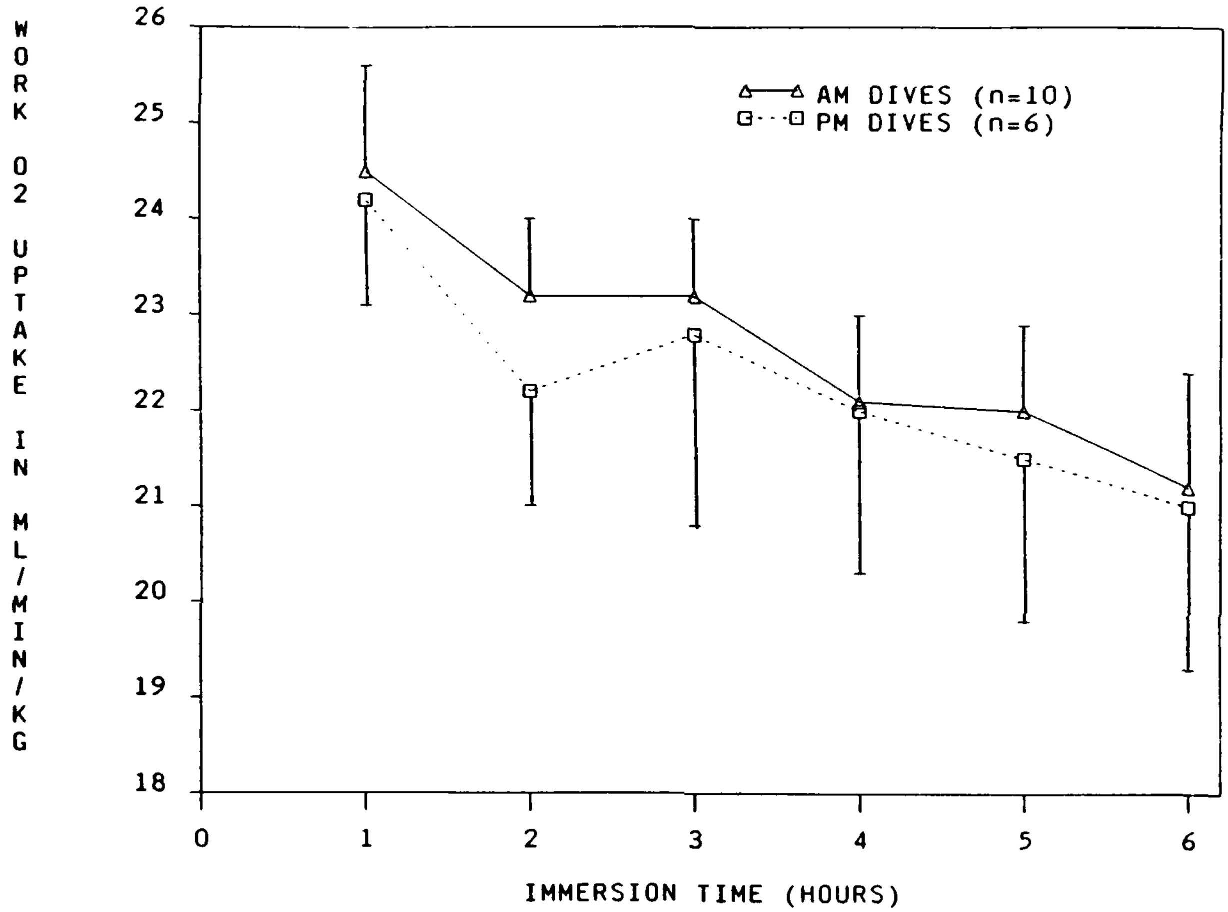

Figure 7. Decline in work O_2 consumption (exercise $\dot{V}_{O_2}$ - resting $\dot{V}_{O_2}$) was similar between A.M. and P.M. immersions. Data represent those subjects who completed the full 6 hour immersion profile.

At 3 hours, the slope of HR versus workload averaged 0.8 ± 0.1 bpm/watt for AM, and 0.7 ± 0.1 for PM immersions. These values were not significantly different from those obtained with hourly exercise (Series 1), nor different from slopes obtained at the 6th hour.

During AM immersions the calculated value of PWC170 was 1.61 ± 0.34 W/kg at 3 h and 1.35 ± 0.23 at 6 h ($F=4.69$, $p=0.08$, $n=6$). A similar finding was made for the PM immersions, with PWC170 averaging 1.50 ± 0.22 W/kg at the 3rd hour and 1.36 ± 0.08 at the 6th hour ($F=2.41$, $p=0.18$, $n=6$). There were no significant differences between AM and PM values.

The PWC170 values were compared to the corresponding hour values from Series 1. No significant differences were found for the values at 3 h between Series 1 and 2 for either AM (1.67 ± 0.13, n=13 vs 1.71 ± 0.18, n=14) or PM immersions (1.57 ± 0.09, n=11 vs 1.59 ± 0.14, n=13). Comparison of values at the 6th hour revealed a significant difference between Series 1 and 2 for AM immersions (1.45 ± 0.09, n=10 vs 1.12 ± 0.03, n=4; $t=2.32$, $p<0.05$) but not for PM (1.45 ± 0.13, n=5 vs 1.36 ± 0.07, n=6).

There was a small, but significant, decrease in work $\dot{V}_{O_2}$ (exercise $\dot{V}_{O_2}$ - rest $\dot{V}_{O_2}$) at 90 W from the 3rd to the 6th hour of immersion in Series 2. This decrease was about half the magnitude of decreases noted in Series 1 for the 1st to 6th hours of immersion. For the AM immersions in Series 2, the work $\dot{V}_{O_2}$ declined from 1.745 ± 0.044 l/min to 1.601 ± 0.027 ($F=7.37$, $p=0.04$, $n=6$) between the 3rd and 6th hours of immersion. The magnitude of this change averaged 0.144 ± 0.053 ℓ of O_2, or about 3,014 J. Work $\dot{V}_{O_2}$ during PM immersions decreased from 1.748 ± 0.099 l/min to 1.631 ± 0.069 ($F=7.578$, $p=0.04$, $n=6$). This decline of 0.118 ± 0.043 ℓ of O_2 represented about 2,470 J.

Reasons for the declines in PWC170 in both series could be linked to hypothermia and reduction in plasma volume. Net decreases in rectal temperature for subjects completing the full 6 h in Series 1 averaged 1.0 ± 0.2 °C (n=10) and 0.9 ± 0.1 °C (n=6) for AM and PM, respectively. Similarly, rectal temperature over 6 h for Series 2 declined 0.8 ± 0.3 °C (n=6) and 1.3 ± 0.4 °C (n=6) for AM and PM, respectively. There were no statistically significant differences between the 2 groups with respect to rectal temperature changes over 6 h.

The immersion-induced diuresis resulted in pronounced dehydration in both groups of subjects. Among all subjects, plasma volume decreased 17.3 ± 1.1% and 16.9 ± 1.3% for all AM and PM immersions, respectively (15). No differentiation was found between time of day or series.

DISCUSSION

This report quantifies changes in the response to submaximal exercise during long duration cold water exposures in divers wearing passive thermal protection. While the dry suits afforded enough thermal protection for about half the dives to be completed for 6 h in 5 °C water (13), the data presented herein indicate that the identical workload became physiologically more demanding as dive time increased.

The linear rise in HR with increments in submaximal workloads provides an index of cardiac responsiveness to exercise. The absence of a change in the slope of this relationship during immersion indicated cardiac responsiveness to a step change in workload did not change. However, the uniform HR increases with exposure time at each workload would suggest a cardiac compensation occurring during the course of immersion. This compensation would be required if the normal exercise HR was insufficient to maintain cardiac output. Plasma volume decreased an average of 17% in the present study (15), a factor that could potentially reduce stroke volume, thereby necessitating a corresponding rise in HR to achieve the required cardiac output.

The use of HR to generate the PWC170 index is a convenient method to quantify an exercise response (14), especially temporal changes within a subject. The 16-19% reduction in PWC170 over the course of 6 h suggests a decrease in cardiac stroke volume of a similar magnitude, and correlates nicely with our measured loss of plasma volume (15).

Subjects who performed the 3 h resting immersion prior to their first exercise period had similar changes in HR, PWC170, and $\dot{V}_{O_2}$ as their Series 1 counterparts. Thus, up to 3 h of immersion, the frequency of exercise had little affect on performance. However, when the subjects rested for an additional 3 hours their performance was noticeably reduced when compared to those doing hourly exercise. While the present study was not designed to factor out reasons for this latent reduction in exercise tolerance, a greater net heat loss was measured in the Series 2 subjects who had greater periods of inactivity.

Resting $\dot{V}_{O_2}$ levels increased linearly throughout the immersions, reflecting a thermogenic response to cold water mediated largely by muscular shivering. The parallel rise in $\dot{V}_{O_2}$ during 50 W exercise would suggest that thermogenesis at this level of cold stress could not be suppressed by this level of activity.

At higher workloads, exercise $\dot{V}_{O_2}$ did not change with time. Thus, calculation of the amount of O_2 contributing to the work effort declined since resting values were increasing progressively. At first glance this finding would give the impression that aerobic efficiency actually increased, since efficiency is defined by the ratio of energy expended to work achieved. A priori reasoning would render this premise unlikely under the harsh environmental conditions of this study.

It is more probable that such apparent decreases in aerobic work could be explained by the interplay of two distinct events. The first event is that the metabolic heat produced by exercise could supply enough heat to obviate the need for shivering thermogenesis. The results of the present study indicate that sufficient heat could not be supplied by 50 W workloads, thus the thermogenic response could persist at this exercise level. Workloads at 70 and 90 W appeared to generate sufficient heat to temporarily compensate for the thermogenic rise in $\dot{V}_{O_2}$.

The second possibility is that the relative amount of work energy from anaerobic metabolism increased during immersion. That is, for a fixed energy requirement, more energy was derived from pathways not utilizing oxygen. Thus, measured work $\dot{V}_{O_2}$ would decline. In support of this distinct event is the finding that venous lactate levels were elevated in our other cold water studies, and similar increases in lactate were measured by other investigators (2,16). We have no evidence to define why cold water exposure raises lactate levels, but one could speculate that changes in muscle perfusion or substrate utilization might contribute to an increase in anaerobic metabolism. It is important to recall the well known inverse relation of lactate to endurance time.

In summary, exercise HR in thermally protected divers increases with each hour of immersion in 5 °C water. By the 6th h of immersion peak HR at 90 W is greater than 80% of their maximum rate. It is well documented that endurance is substantially reduced at this HR level. Part of the uniform increases in HR could be ascribed to dehydration, measured as a reduction in plasma volume with an attendant decrease in cardiac stroke volume. Oxygen consumption at a light workload rose temporally at a rate similar to resting values, indicating this workload did not generate enough metabolic heat to compensate the thermogenic response to cold water. At higher workloads, $\dot{V}_{O_2}$ did not change with time of immersion. It is hypothesized that this latter finding may be due to either generating sufficient heat to compensate the thermogenesis, or possibly due to an increase in the anaerobic contribution to work.

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APPENDIX A

PHYSICAL CHARACTERISTICS OF DIVERS

SUBJ. NO.	AGE (yr)	HT (cm)	WT (kg)	% FAT	$\dot{V}_{O_2}$ max ml/min/kg, STPD	HR max* bpm	PWC170, DRY W/kg
1	30	170	78.20	13	44	186	3.29
2	26	183	77.20	11	50	192	4.37
3	24	185	81.20	9	45	186	3.66
4	26	185	80.64	9	47	186	3.93
5	25	173	72.91	10	--	---	3.33
6	26	170	75.42	16	40	214	3.94
7	31	180	81.36	12	50	188	2.83
8	25	178	81.18	14	46	204	2.45
9	23	178	78.31	10	52	188	3.74
10	32	170	71.48	8	41	172	4.91
11	32	178	73.90	11	48	192	2.44
12	29	188	87.10	22	40	188	4.25
13	23	193	90.10	14	49	168	3.77
14	33	180	73.08	11	48	192	2.78
15	29	183	84.82	18	42	192	2.56
16	26	185	85.84	13	45	188	4.15
mean	28	180	79.55	13	46	189	3.53
S.E.	±1	± 2	±1.38	±1	±1	± 3	±0.19

*Determined in dry laboratory with incremental bike workloads

NOTES: 1) Subjects 1-8 in Series 1, 9-16 in Series 2

2) % fat determined by hydrostatic weighing

3) PWC170 derived from 50, 70, 90 W workloads

APPENDIX B

SERIES 1, AM IMMERSION

	SUBJ	REST HR	REST $\dot{V}_{O_2}$	50 W HR	50 W $\dot{V}_{O_2}$	70 W HR	70 W $\dot{V}_{O_2}$	90 W HR	90 W $\dot{V}_{O_2}$	PWC170
CHO DIET	1	96	5	114	22	136	25	140	30	1.79
HOUR 1	2	---	9	---	27	---	29	---	33	----
	3	90	5	120	22	138	24	150	29	1.42
	4	72	6	108	25	126	29	138	32	1.63
	5	60	6	96	20	132	29	156	32	1.39
	6	72	6	114	22	132	26	144	28	1.64
	7	72	7	96	22	102	22	120	26	2.17
	8	96	6	126	--	144	--	162	--	1.22
HOUR 2	1	72	4	126	23	132	25	150	30	1.62
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	90	5	120	24	126	28	138	29	2.02
	5	60	6	120	25	126	28	156	32	1.34
	6	72	6	120	21	132	25	150	30	1.56
	7	66	5	96	29	102	23	114	26	2.66
	8	102	6	120	22	138	24	150	26	1.42
HOUR 3	1	72	6	114	23	132	25	141	27	1.58
	2	---	--	---	--	---	--	---	--	----
	3	90	9	120	24	132	27	150	31	1.45
	4	96	7	114	26	126	27	138	29	1.78
	5	72	8	120	32	138	29	156	33	1.45
	6	96	6	126	25	138	26	162	31	1.34
	7	66	6	102	21	112	22	120	25	2.55
	8	90	6	120	21	144	24	162	26	1.19
HOUR 4	1	96	7	138	23	144	25	156	31	1.58
	2	---	--	---	--	---	--	---	--	----
	3	90	8	120	23	138	27	144	31	1.60
	4	96	7	120	25	126	27	150	31	1.50
	5	72	6	114	25	132	27	150	32	1.54
	6	---	--	---	--	---	--	---	--	----
	7	72	6	102	23	114	23	126	25	2.01
	8	96	8	120	21	138	26	156	28	1.30
HOUR 5	1	90	6	126	24	144	26	150	30	1.53
	2	---	--	---	--	---	--	---	--	----
	3	78	8	120	24	138	26	150	30	1.42
	4	78	8	126	25	138	27	144	30	1.81
	5	72	9	108	25	138	28	150	32	1.46
	6	---	--	---	--	---	--	---	--	----
	7	72	7	128	26	114	25	138	31	1.68
	8	96	10	126	24	144	25	162	27	1.22

HOUR 6	1	78	8	132	24	150	26	168	30	1.18
	2	---	--	---	--	---	--	---	--	----
	3	108	9	120	28	132	29	138	33	1.96
	4	84	9	120	25	132	26	150	31	1.46
	5	72	9	120	22	138	23	162	26	1.35
	6	---	--	---	--	---	--	---	--	----
	7	---	--	---	--	---	--	---	--	----
	8	90	8	120	24	138	24	156	27	1.30
MIX DIET HOUR 1	1	66	4	120	23	132	26	144	29	1.71
	2	78	5	108	25	126	28	132	33	1.94
	3	---	4	---	18	---	23	---	25	----
	4	48	4	108	23	120	26	132	30	1.90
	5	60	7	102	24	114	28	126	30	2.24
	6	60	5	102	20	114	23	132	27	1.88
	7	72	5	96	21	102	21	114	27	2.66
	8	78	7	120	22	138	28	162	31	1.21
HOUR 2	1	90	6	120	22	132	25	150	29	1.51
	2	84	7	108	25	114	27	132	33	2.03
	3	---	6	---	20	---	24	---	26	----
	4	96	6	108	21	126	27	144	30	1.47
	5	78	10	108	27	120	30	132	36	2.10
	6	66	6	102	18	126	22	150	28	1.41
	7	54	7	96	21	102	24	114	29	2.66
	8	96	8	126	26	144	28	150	31	1.48
HOUR 3	1	90	5	120	21	138	25	156	30	1.35
	2	---	--	---	--	---	--	---	--	----
	3	---	6	---	22	---	23	---	27	----
	4	84	9	114	23	120	26	138	28	1.82
	5	72	9	102	30	126	35	138	38	1.69
	6	54	7	108	22	126	24	144	28	1.58
	7	66	7	96	20	102	24	114	29	2.66
	8	84	7	126	23	144	25	162	28	1.22
HOUR 4	1	---	--	---	--	---	--	---	--	----
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	84	7	114	29	132	29	138	30	1.74
	5	78	8	108	27	114	28	132	36	2.15
	6	60	8	126	23	144	26	162	28	1.31
	7	72	9	96	27	108	28	120	30	2.13
	8	78	8	138	23	150	25	168	28	1.16
HOUR 5	1	---	--	---	--	---	--	---	--	----
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	84	8	120	22	132	25	150	29	1.46
	5	60	10	108	28	120	29	132	37	2.10
	6	96	7	120	20	138	23	162	29	1.31
	7	60	8	108	18	110	24	120	30	2.24
	8	90	8	132	22	150	24	168	26	1.14

HOUR 6	1	---	--	---	--	---	--	---	--	----
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	108	8	114	25	130	25	150	28	1.40
	5	96	10	108	29	120	32	144	38	1.66
	6	78	7	126	21	144	23	162	28	1.31
	7	72	8	96	22	108	26	126	29	1.84
	8	102	8	144	23	156	26	174	26	1.06

REST values obtained 10 min prior to start exercise

HR expressed in beats/min

$\dot{V}_{O_2}$ expressed in ml/min/kg, STPD

PWC170 calculated from exercise HR data

APPENDIX C

SERIES 1, PM IMMERSION

	SUBJ	REST HR	REST $\dot{V}_{O_2}$	50 W HR	50 W $\dot{V}_{O_2}$	70 W HR	70 W $\dot{V}_{O_2}$	100 W HR	100 W $\dot{V}_{O_2}$	PWC170
CHO HOUR 1	1	72	5	120	--	138	--	150	--	1.47
	2	72	6	108	--	120	25	138	31	1.73
	3	66	6	120	20	132	24	144	27	1.64
	4	68	6	---	--	---	--	---	--	----
	5	66	5	102	24	114	28	---	--	----
	6	72	6	108	23	126	25	150	26	1.46
	7	72	5	102	23	108	26	120	29	2.50
	8	84	8	120	22	138	25	162	28	1.21
HOUR 2	1	84	5	132	24	138	25	156	29	1.49
	2	66	8	120	27	126	28	132	29	1.80
	3	72	10	108	21	126	27	144	29	1.46
	4	72	7	114	27	126	29	144	28	1.56
	5	70	10	---	--	---	--	---	--	----
	6	60	6	126	26	144	28	156	29	1.42
	7	72	7	102	25	114	26	120	27	2.44
	8	102	6	120	23	138	26	156	28	1.30
HOUR 3	1	96	6	138	23	156	33	168	35	1.17
	2	--	11	---	--	---	--	---	--	----
	3	84	8	114	26	132	26	132	31	1.52
	4	90	8	120	32	132	26	138	31	1.97
	5	--	--	---	--	---	--	---	--	----
	6	72	6	126	23	128	24	162	28	1.34
	7	78	8	108	24	114	25	132	29	1.93
	8	90	8	120	21	132	25	162	34	1.24
HOUR 4	1	96	9	144	33	160	34	168	36	1.17
	2	78	11	120	28	138	33	150	35	1.49
	3	80	9	---	--	---	--	---	--	----
	4	--	--	---	--	---	--	---	--	----
	5	--	--	---	--	---	--	---	--	----
	6	--	--	---	--	---	--	---	--	----
	7	78	8	108	24	120	25	138	29	1.65
	8	96	9	120	22	138	24	162	29	1.21
HOUR 5	1	—	7	---	30	---	30	---	32	----
	2	72	10	114	28	126	30	150	30	1.48
	3	--	--	---	--	---	--	---	--	----
	4	--	--	---	--	---	--	---	--	----
	5	--	--	---	--	---	--	---	--	----
	6	--	--	---	--	---	--	---	--	----
	7	78	9	114	24	120	25	132	28	2.17
	8	--	--	---	--	---	--	---	--	----

HOUR 6	1	--	--	---	--	---	--	---	--	----
	2	72	10	114	27	138	31	144	30	1.46
	3	--	--	---	--	---	--	---	--	----
	4	--	--	---	--	---	--	---	--	----
	5	--	--	---	--	---	--	---	--	----
	6	--	--	---	--	---	--	---	--	----
	7	78	9	114	22	120	24	138	29	1.80

MIX HOUR 1	1	84	5	120	19	134	22	144	28	1.69
	2	90	6	114	32	120	30	132	32	2.29
	3	84	6	114	--	126	--	132	--	2.12
	4	60	6	114	23	132	30	144	36	1.53
	5	78	5	90	23	102	28	114	34	2.51
	6	72	5	114	23	138	28	144	31	1.60
	7	60	5	102	21	108	24	120	26	2.55
	8	84	7	120	22	132	24	156	28	1.33
HOUR 2	1	96	6	132	17	138	20	150	24	1.75
	2	72	10	114	30	132	32	138	33	1.81
	3	90	5	110	--	126	--	144	--	1.49
	4	96	5	126	23	132	27	138	31	1.43
	5	54	7	96	26	108	31	126	34	2.06
	6	84	7	114	20	132	25	144	31	1.64
	7	72	5	102	20	108	24	126	29	2.09
	8	84	6	120	20	132	25	150	28	1.45
HOUR 3	1	96	5	126	23	132	25	150	23	1.60
	2	84	11	120	30	126	29	132	32	1.81
	3	90	6	114	--	126	--	144	--	1.55
	4	90	7	120	27	132	28	144	31	1.65
	5	60	8	96	27	108	29	126	31	2.06
	6	74	6	---	--	---	--	---	--	----
	7	60	5	90	20	102	27	120	29	1.94
	8	90	8	120	21	132	26	162	26	1.24
HOUR 4	1	106	8	150	--	156	20	168	25	1.24
	2	86	12	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	78	9	126	27	132	28	144	31	1.56
	5	60	9	96	27	114	35	138	33	1.67
	6	---	--	---	--	---	--	---	--	----
	7	70	7	102	20	114	25	132	28	1.75
	8	90	9	120	21	132	22	156	27	1.33
HOUR 5	1	90	7	138	21	150	26	156	30	1.52
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	72	8	114	23	132	29	144	29	1.53
	5	---	--	---	--	---	--	---	--	----
	6	---	--	---	--	---	--	---	--	----
	7	80	8	---	--	---	--	---	--	----
	8	96	9	126	21	144	23	162	25	1.22

HOUR 6	1	78	7	150	25	156	27	166	27	1.30
	2	---	--	---	--	---	--	---	--	----
	3	---	--	---	--	---	--	---	--	----
	4	84	8	114	26	132	28	144	30	1.53
	5	---	--	---	--	---	--	---	--	----
	6	---	--	---	--	---	--	---	--	----
	7	---	--	---	--	---	--	---	--	----
	8	102	11	132	27	156	--	174	28	1.05

REST values obtained 10 min prior to start exercise

HR in beats/min

$\dot{V}_{O_2}$ in ml/min/kg

PWC170 calculated from exercise HR data

APPENDIX D

SERIES 2, AM IMMERSION

	SUBJ	REST HR	REST $\dot{V}_{O_2}$	50 W HR	50 W $\dot{V}_{O_2}$	70 W HR	70 W $\dot{V}_{O_2}$	90 W HR	90 W $\dot{V}_{O_2}$	PWC170
CHO HOUR 3	9	78	9	114	22	114	27	126	29	3.11
	10	60	7	102	23	120	28	132	30	1.95
	11	102	9	132	27	144	29	150	32	1.79
	12	72	8	114	20	138	26	156	30	1.18
	13	78	6	108	22	108	24	132	34	1.78
	14	120	9	144	26	162	29	174	32	1.14
	15	102	7	126	25	144	24	162	28	1.17
	16	--	--	---	--	---	--	---	--	----
HOUR 6	9	--	--	---	--	---	--	---	--	----
	10	--	--	---	--	---	--	---	--	----
	11	--	--	---	--	---	--	---	--	----
	12	--	--	---	--	---	--	---	--	----
	13	--	--	---	--	---	--	---	--	----
	14	102	11	144	30	162	33	174	34	1.14
	15	90	9	132	27	150	25	168	28	1.09
	16	--	--	---	--	---	--	---	--	----
MIX HOUR 3	9	96	7	108	24	114	26	120	29	3.28
	10	72	8	108	27	120	27	150	31	1.57
	11	108	6	120	23	138	27	156	30	1.43
	12	84	7	108	19	126	26	156	29	1.19
	13	78	7	102	21	108	22	126	27	1.85
	14	84	7	120	24	144	29	156	29	1.41
	15	96	8	132	21	144	25	162	30	1.20
	16	--	--	---	--	---	--	---	--	----
HOUR 6	9	90	11	114	27	120	26	132	30	2.48
	10	--	--	---	--	---	--	---	--	----
	11	102	8	150	28	162	32	174	34	1.13
	12	--	--	---	--	---	--	---	--	----
	13	--	--	---	--	---	--	---	--	----
	14	84	9	138	27	162	29	168	32	1.21
	15	114	9	144	24	162	28	168	27	1.06
	16	--	--	---	--	---	--	---	--	----

REST values obtained 10 mn prior to start exercise

HR expressed in beats/min, $\dot{V}_{O_2}$ in ml/min/kg

PWC170 calculated from exercise HR data

APPENDIX E

SERIES 2, PM IMMERSION

	SUBJ	REST HR	REST $\dot{V}_{O_2}$	50 W HR	50 W $\dot{V}_{O_2}$	70 W HR	70 W $\dot{V}_{O_2}$	90 W HR	90 W $\dot{V}_{O_2}$	PWC170
CHO	9	90	7	108	20	114	25	156	26	1.36
HOUR 3	10	84	9	96	--	---	--	---	--	----
	11	120	5	126	25	138	28	156	35	1.49
	12	72	7	120	19	138	23	156	28	1.21
	13	--	--	---	--	---	--	---	--	----
	14	108	8	138	24	156	30	168	35	1.25
	15	90	7	126	23	138	25	162	29	1.19
	16	--	--	---	--	---	--	---	--	----
HOUR 6	9	--	--	---	--	---	--	---	--	----
	10	--	--	---	--	---	--	---	--	----
	11	--	--	---	--	---	--	---	--	----
	12	90	9	114	20	138	24	156	28	1.18
	13	--	--	---	--	---	--	---	--	----
	14	--	--	---	--	---	--	---	--	----
	15	--	--	---	--	---	--	---	--	----
	16	--	--	---	--	---	--	---	--	----
MIX	9	72	7	108	23	114	24	126	29	2.43
HOUR 3	10	78	8	108	26	114	27	126	30	2.66
	11	108	9	114	27	132	30	150	32	1.52
	12	96	7	120	22	138	27	150	32	1.32
	13	78	7	108	25	114	21	126	24	2.11
	14	108	8	126	26	144	27	156	28	1.47
	15	108	6	144	21	156	24	168	28	1.10
	16	90	10	132	25	138	26	150	29	1.59
HOUR 6	9	--	--	---	--	---	--	---	--	----
	10	--	--	---	--	---	--	---	--	----
	11	84	10	126	17	144	24	162	28	1.18
	12	--	--	---	--	---	--	---	--	----
	13	84	8	108	24	120	26	132	28	1.70
	14	84	9	126	26	156	29	162	27	1.29
	15	114	8	132	16	144	25	156	27	1.34
	16	114	10	132	26	150	28	156	30	1.28

REST values obtained 10 min prior to start exercise

HR expressed in beats/min, $\dot{V}_{O_2}$ in ml/min/kg

PWC170 calculated from exercise HR data

APPENDIX F

LAY LANGUAGE SUMMARY OF OPERATIONAL RELEVANCE

The present study assessed how well a diver can perform leg work during the course of 6 hours in 5 °C (41 °F) water at a depth of 6.1 msw (20 fsw). The study was subdivided to determine: 1) if time of day influenced work capacity (1000 vs 2200 hours), 2) if hourly exercise was better than 3 hours of rest between exercise bouts.

During each immersion divers work a dry suit outer garment with M-800 Thinsulate undergarments, dry gloves, and a full face mask. The breathing gas was air. A total of 16 U.S. Navy divers were studied (12 Saturation divers, 4 SEALs). Half the divers performed 9 min of submaximal leg exercise once each hour, while the other 8 divers performed the same work only at the 3rd and 6th hours of immersion.

Each diver performed 2 immersions in the wetpot during the course of one 5-day air saturation dive, one beginning at 1000 and one beginning at 2200. Elapsed time between immersions was 54 hours. After a one week interval, each diver participated in a second saturation dive where the order of starting immersion times was reversed.

Over the course of 6 hours, a 20% increase in heart rate was required to achieve the same work. By the 6th hour of immersion, divers were working at 80-85% of their maximum heart rate. At that level of work intensity one could predict that endurance time would be significantly reduced.

Based on oxygen consumption data, the level of the leg work was similar to swimming at speeds up to about 0.6-1.5 knots. Early in a dive, up to about 3 hours, this work level could be sustained for reasonable periods (perhaps

30-60 min). However, endurance time would be much less after 3 hours at this intensity.

If the divers were at rest for 3 hours prior to the exercise, they could work at the same level same as divers working at an hourly schedule. Such a scenario might be envisioned during a SEAL Delivery Vehicle (SDV) transit to a target. However, if the same divers rested for an additional 3 hours, simulating the SDV transit back to base, their work level would be reduced more than those doing more frequent exercise.

The data also suggest that in order to generate enough metabolic heat to offset the effects of cold water a diver would have to work at an oxygen consumption of 1.0-1.5 l/min. Endurance time at this intensity would depend in part on individual diver's fitness. Lesser thermal protection, like a wet suit, would likely require greater work levels.

There was no difference in work performance between immersions starting at 1000 and at 2200 hours. The increased physiological cost of work noted during immersion was correlated with moderate hypothermia and marked dehydration.

The present results indicate that a diver can remain immersed in 5 °C water for periods up to 6 hours. However, his work tolerance may be substantially reduced in direct proportion to dive time. Therefore considerations of how much useful work can be achieved versus time of exposure need to be factored in mission planning.